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Cooling with renewable energy

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Tiivistelmä

Tämä opinnäytetyö on osa Kaakkois-Suomen ammattikorkeakoulun TKI-hanketta, jonka tarkoitus oli tutkia ja kehittää menetelmiä kiinteistöjen, teollisuuden prosessien ja toimitilojen jäähdytykseen. Hankkeen tarkoituksena oli ilmastonmuutoksen myötä nouseviin lämpötiloihin sopeutuminen ja kasvavan jäähdytystarpeen kattaminen kestävästi muun muassa uusiutuvan energian avulla. Tämän opinnäytetyön painopiste oli jäähdytyksen toteutuksessa uusiutuvalla energialla, jonka käyttöönotto nousee yhä välttämättömämmäksi ilmastonmuutoksen edetessä.

Tämän toteuttamiseksi tässä työssä keskitytttiin pääasiassa jäähdytyksen ja uusiutuvan väliseen rajapintaan. Ensimmäiseksi tarkasteltiin jäähdytyksessä yleisimmin tekniikoita ja niiden käyttötapoja, sillä olemassa olevan teknologian käyttö on ilmastonmuutoksen kannalta nopeampi ja edullisempi ratkaisu kuin täysin uudenlaisen, joskin tehokkaamman, tekniikan kehittäminen. Toisena analysoitiin sähköllä tapahtuvan jäähdytyksen toteuttamisvaihtoehtoja siihen sopivilla uusiutuvan energian muodoilla ja etsittiin mahdollisia ratkaisuja vastaantuleviin haasteisiin. Kolmantena arvioitiin lämmöllä tapahtuvan jäähdytyksen toteutusta vastaavalla tavalla. Lopuksi katsastettiin kohteita, joissa uusiutuvalla energialla on merkittävä osuus kohteiden jäähdytyksessä ja analysoitiin ratkaisujen sopivuutta Suomen olosuhteisiin. Työn ulkopuolelle on jätetty rakennustekniikkaan ja ympäristösuunnitteluun liittyvät ratkaisut.

Opinnäytetyön tuloksena saatiin perusteellinen läpileikkaus uusiutuvan energian ja jäähdytyksen välisestä suhteesta ja niistä keinoista, joilla ne voidaan yhdistää. Tulokset tiivistettiin taulukoihin, jotka esittävät saadut edut ja mahdolliset haasteet. Nykyiset tavat jäähdyttää ovat pitkälle kehittyneitä ja sovellettavissa moneen käyttöön. Uusiutuva energia on myös pääsemässä eroon vanhoista heikkouksistaan, kuten korkeasta hinnastaan. Suurimmat haasteet ovat näiden kahden rajapinnalla tapahtuva energian muutos ja uusiutuvan energian perusongelman, luotettavuuden, parantaminen. On myös muistettava, että parhaiden tulosten saamiseksi on käytettävä kuhunkin tilanteeseen sopivaa jäähdytyksen ja energianlähteen yhdistelmää ja pidettävä hybridivaihtoehdot käytössä niiden monimutkaisuudesta huolimatta.

Asiasanat

uusiutuva energia, jäähdytys, kylmätekniikka, kestävä kehitys

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Abstract

This thesis is a part of the Southeast Finland University's RDI project which aims at studying and developing methods for cooling real estates, industrial processes and premises. The goal of the project was to adapt the rising temperatures due to climate change and to cover the growing need for cooling through renewable energy. The focus of this thesis is on the implementation of cooling with renewable energy. Its implementation becomes increasingly necessary as climate change advances.

As a result of the thesis, a summary was produced about the use of renewable energy in cooling and the ways in which they can be combined. Firstly, the most commonly used techniques for cooling are considered, as the use of existing technology is a quicker and more affordable solution to fight against climate change than the development of a completely new, yet more effective, technology. Secondly, the task is to analyse the alternatives for the implementation of electric cooling with suitable forms of renewable energy and possible solutions to emerging challenges. Thirdly, the implementation of heat cooling is evaluated in a similar way. Finally, the facilities using renewable energy in cooling are examined and the suitability of the solutions for conditions in Finland is analysed. Solutions to construction engineering and environmental design are excluded.

The thesis resulted in a review using renewable energy in cooling and the ways in which they can be combined. The results were combined to charts, which show the acquired benefits and possible challenges. Existing ways of cooling are highly sophisticated and applicable to many uses. Renewable energy is also eliminating its old weaknesses, such as its high price. The most significant challenges are in the energy efficiency and in the improvement of renewable energy availability based on demand. To obtain the best results, a combination of cooling and energy sources appropriate to each situation are recommended. The hybrid alternatives could be considered where they are appropriate.

Keywords

renewable energy, refrigeration, cooling, sustainable development

SISÄLLYS

1 INTRODUCTION

Intergovernmental Panel on Climate Change (IPCC) published in October 8th 2018 its fifth assessment report, according to which “man-made climate change reached about 1°Celsius compared to pre-industrial time, currently rising 0.2°C in a decade” (Koistinen 2018; IPCC 2018). According to the same report “if current speed of rising temperatures continues, the world would experience 1.5 Celsius of warming due to human action around 2040”. In Finland the Finnish meteorological institute has stated that climate change would increase the strength of storms, increases flooding around large lakes, turn winters darker and makes extreme weather events more common alongside rising temperatures. It is clear, that in order to restrain the climate change and stop it, more actions must be taken and at the same time adjust there is a need adjust to the changes it brings.

The goal of this thesis is to investigate one option that follows the principals of sustainable development from the energy production point of view and use. Air conditioning consumes already a significant portion of energy use in tropical climates. If climate changes as predicted, demand for cooling will increase greatly in the future in colder climates too, such as in Finland. Renewable energy, such as solar, wind and biomass, could provide relief in heat and compensate the problems of increasing demand and advance sustainable energy usage. Because the various options are not created equal, researching these possibilities beforehand will help to avoid many problems during their commissioning.

To achieve this goal, literature research, research analysis and calculations are utilized to find the benefits and disadvantages and their status in terms of use and feasibility. The results are presented through a mathematic example, one existing application and a table of properties of different refrigeration technologies and renewable energy forms. This work won’t cover cryogenics that refers to applications under -150 degrees Celsius, as that technology is outside the expertise of an energy engineer and requires arrangements more fitting to laboratory conditions and specific industries. It’s also not used for cooling buildings, so going into its details would be redundant.

2 COOLING TECHNIQUES

In buildings cooling is meant to keep the temperature of spaces as low as is needed for its purpose. This temperature can be anything from the normal room temperature (21 degrees Celsius) to -40 degrees Celsius in rapid freezing of food products (Helsingin kaupunki 2015). In order to benefit as much as possible, the used system must be suitable for its purpose. This creates demands that depends on the goal. Some of these, such as efficiency, are common to all systems. However, many systems have special requirements that need their own answers. In hospitals the cooling must be absolutely reliable. The local price of biofuels affects what system is chosen. Some systems can be fitted to old buildings, others can't be. The size of the space alone can make some systems suitable while making others too small.

Cooling makes only a limited fraction of Finland's overall energy consumption as annual average temperatures remain under 10 degrees Celsius. Finnish meteorological institute states that based on annual statistics Helsinki's average temperature has been below 6 degrees Celsius between 1981-2010. This is lower than the temperatures where air conditioning is normally being used. (Ilmatieteen laitos 2018.) One way to put this into context is the definition Statistics Finland uses: "Electricity consumed by heat pumps, both in cooling and heating usage, is included in electricity used in heating in this evaluation". Based on this cooling's role in Finland's energy consumption is, at least currently, too small to be separated in statistics. However, one shouldn't build their plans on these statistics due to climate change. (Suomen virallinen tilasto (SVT) S.a.)

Commercially refrigeration has a significant role though, as many businesses need refrigeration technology to operate:

- Ice hockey is in Canada 11.2 billion Canadian dollar trade (Scotia Bank 2015).
- Four largest NHL teams are valued over one billion USD, while the whole league is valued over 19.5 billion USD (Forbes 2018).
- 15 best-selling ice cream brands combined sales exceeded 14 billion USD in 2015 and each of them expected their sales to increase in 2016 (Forbes 2016).

Renewable energy is also economically a major business activity which in this context only highlights what renewables can do for cooling:

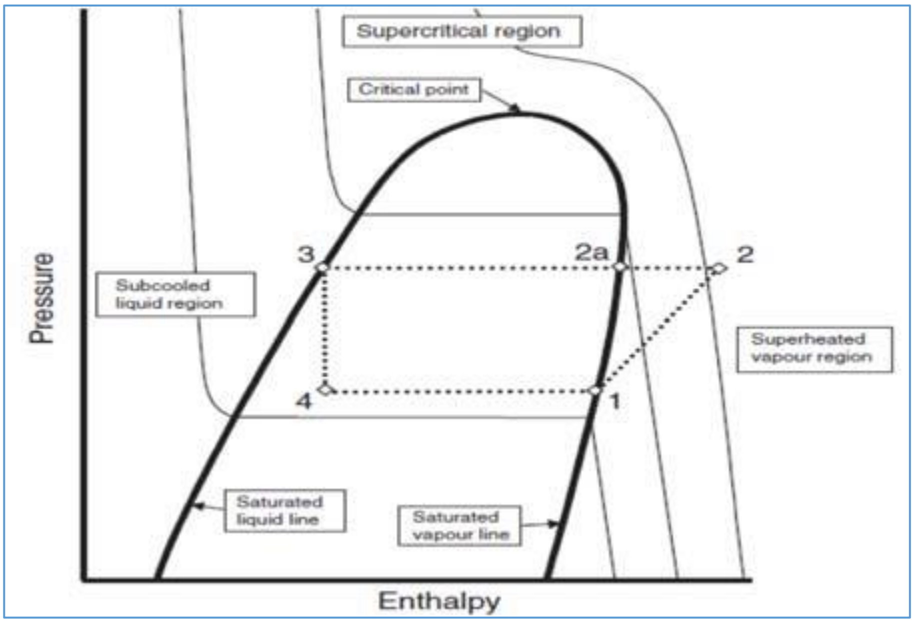
- Turnover has risen over 800 million and added value has come up over 300 million between 2010 and 2016 in renewable energy sector (Ministry of Economic Affairs and Employment of Finland 2017).
- Usage of renewable energy has quickly risen after the turn of the millennium, 16.8% on average in 2006-2016 (BP 2018).

In order to accomplish cooling with renewable energy, the first step is to specify what is currently happening in Finland’s renewable energy sector. Statistics Finland has calculated that 34%, or one third, of total energy consumption was covered using renewables in 2016 (ENERGY IN FINLAND 2017). This covers around 38.7% of Finland’s gross final consumption which fulfils Finland’s EY-goals (Energia 2017 -taulukkopalvelu 2018). As these numbers continue to go up, finding and developing more applications for renewables is a good option next. This and the climate change itself make great arguments for using cooling with renewable energy, especially if its demand keeps only increasing. If so, a classification is needed to specify where renewables are used.

In the textbook “Kylmätekniikka” refrigeration technology has been defined for this purpose: “Refrigeration technology which is also called cryogenics, is an area of technologies in order to maintain object(s) at a lower temperature compared to its environment.” (Aittomäki et al. 1993, 1.) Based on this definition refrigerators, freezers and air conditioners belong under this category. This coincides with the thesis goals, making it a suitable classification for this thesis. Cryogenics which refers to applications kept in temperatures below -150 Celsius, belongs to this definition, but it is left outside of this work. This is because temperatures this low aren’t used anywhere else than in laboratory conditions and in certain industrial processes. Cooling of household appliances is also left out, as most home electronics.

2.1 Compressor refrigerator

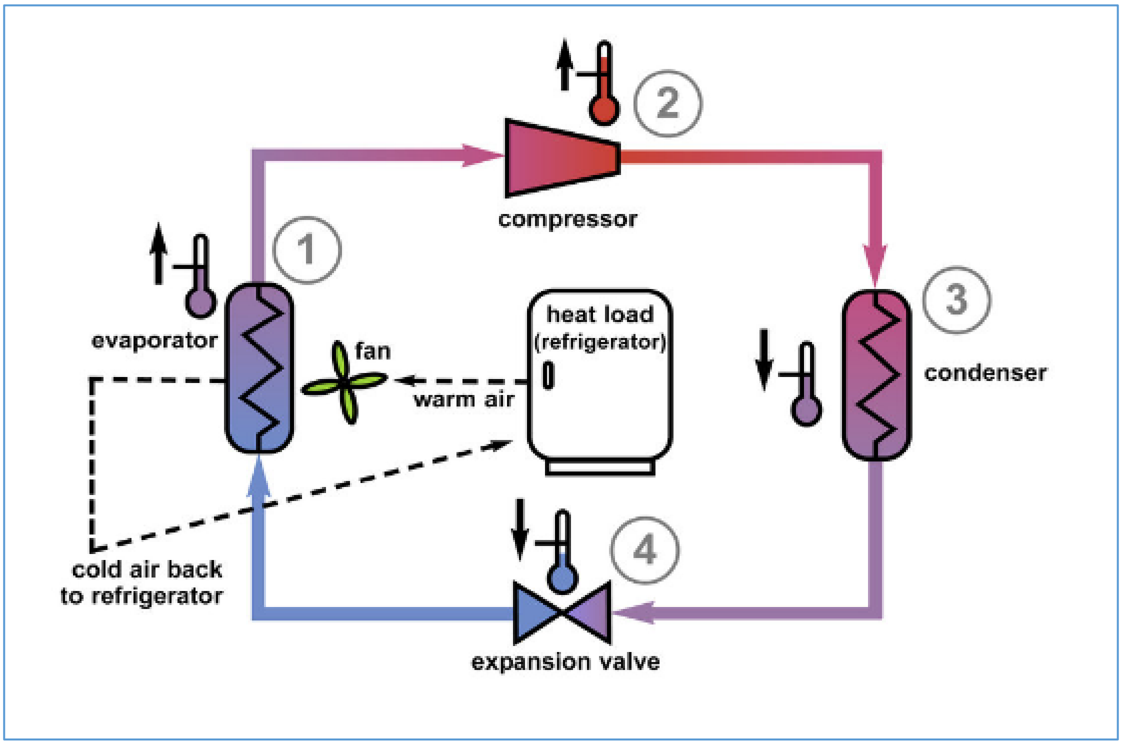
The most common cooling system is a compressor-based refrigerator, freezer or air conditioning device. It is based on refrigerant gas that absorbs and releases heat in a repeating cycle the gas goes through. The picture 1 shows a diagram that describes refrigerant gases changes in pressure and enthalpy during its cycle. These changes in different parts of the cycle are what create the cooling effect. Horizontal axis refers to refrigerants enthalpy and vertical axis refers to pressure.



Picture 1. Refrigerants pressure-enthalpy changes in a compression system. (Setiyo et al. 2017)

1. In the evaporator the refrigerant turns to gas in low pressure, absorbing heat from the environment (Picture 1, points 4-1).
2. The compressor presses the gas into the condenser in higher pressure (Picture 1, points 1-2).
3. The refrigerant releases the heat into the environment under high pressure (Picture 1, points 2-3).
4. The refrigerant loses pressure rapidly inside the expansion valve and the cycle starts from the beginning (Picture 1, points 3-4). (Korhonen 2011, 9.)

A common example is the refrigerator in the picture 2 which is also the most common cooling device. The first number in the list above is the same as in picture 2 to show how the parts of the system work with the refrigerant.



Picture 2. Compressor based refrigerator (National Institute of Standards and Technology 2014)

This technology has been in use since 1834 when Jakob Perkins patented the first compressor refrigerator. It made storing of food for longer periods of time possible which in turn made diets more varying. (Breverton 2012.) During its 200-year history it has become a go-to solution which is usable in a myriad of applications and uses. It is durable enough to stand decades of wear and tear, has a reasonable price, can be run anywhere electricity is available and in a wide temperature range.

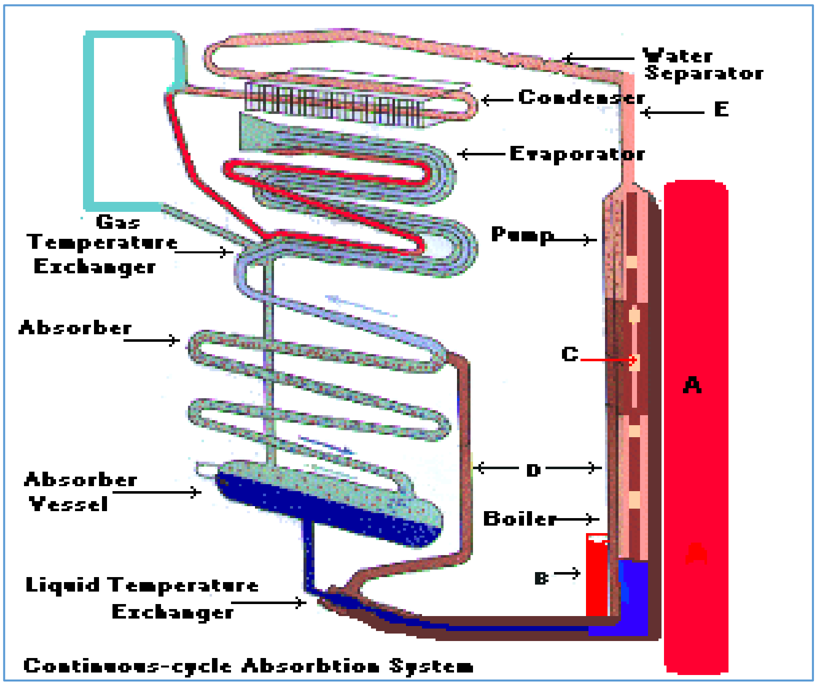
Compressor systems do have their weaknesses, though. It depends on the electricity that rotates the compressor. Electricity is also the only form of the energy this system is able to use, so excess heat from other devices and from the system itself is lost. Old weakness of using CFC compounds, a major cause of ozone depletion, is no longer a problem. In 1985 the Vienna Convention for the Protection of the Ozone Layer and the following Montreal protocol with its additions led to reductions in their use and subsequent reinforcement of the ozone layer (Ympäristöministeriö 2013). Currently the hot topic in research and development is finding new refrigerants that have smaller greenhouse effects. Some alternatives have been found, but there are obstacles in their way from patenting to fire hazards and technical limitations. (Rosenthal & Lehren 2012)

2.2 Absorption refrigerator

An absorption refrigerator is a cooling device that produces cold using heat. Unlike a**d**sorption which is limited to surface level, the a**b**sorption happens in the whole volume of the chemical (Jasuja et al. 2019). Invented in 1922, different versions of this device use heat as their source of power. For this reason, it is suitable where excess heat is available, or some process creates heat as a by-product (Kuningas 2016). Unlike mechanical energy requiring compressor refrigerators, absorption systems are based on chemistry and heat. The basic principle is to use the heat in the area that must be cooled to evaporate refrigerant in low pressure which is then absorbed into the other chemical and transfers the heat away. For this system to work, both chemicals must be able to absorb and separate from each other and the refrigerant must be able to take in heat during evaporation in low pressure.

Ammonia/water-based systems can produce temperatures below zero degrees Celsius, but ammonia is harmful which limits its applications. A combination of lithium bromide and water is much safer but can only produce temperatures of five degrees Celsius. This is equal to a normal refrigerator but it is insufficient for freezers -18 degrees Celsius (Näin tarkastat… 2015). Both systems follow the same operating principle. Other combinations have been tested, but their performance is weaker than the above mentioned. (Koljonen & Sipilä 1998.) The structure of the absorption system is shown in picture 3, showing also how it works.

The absorption refrigerator is filled with water, ammonia and hydrogen in a pressure where ammonia condenses in room temperature. Placed under boiler A or in pocket B, a heater warms up a liquid which bubbles with ammonia. These bubbles lift the weak solution with themselves to a siphon pump C. The weak solution flows to pipe D, while gaseous ammonia rises into the pipe E and its water separator. Water condenses in the water separator and flows back to the boiler, with dry ammonia gas continuing to the condenser, where it cools, cools down to liquid and flows to the evaporator. Hydrogen flows to the evaporator which lowers the pressure enough for ammonia to evaporate, taking heat from the environment. This environment is the space that is meant to be cooled. The mixture of water and ammonia travels from the evaporator to the absorber. The weak solution flows to the absorber's upper part from the pipe D and absorbs ammonia from the mixture. Released hydrogen flows back to the evaporator and strong solution transfers the absorber to boiler A. This closes the loop and the cycle repeats.

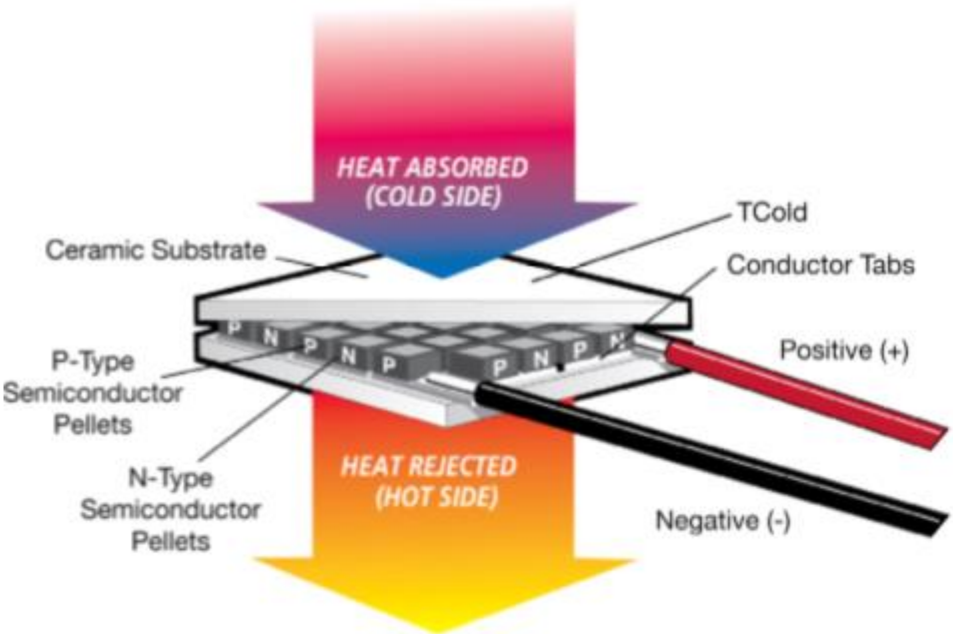


Picture 3. Absorption refrigerator's structure (Carnagie Mellon School of Computer Science s.a)

The greatest weakness of an absorption system is its low coefficient of performance, a measure of how much cold or heat is produced for each unit of energy. In absorption systems this value is below one, meaning that one kilowatt-hour of energy produces less than one kilowatt-hours worth of cooling. It's also unable to operate outside its temperature range which depends on used chemicals. (Crepinsek et al. 2009.)

2.3 Peltier element

The Peltier element gained its name from Jean Charles Athanase Peltier, a French physicist who described the effect the system is based on, in 1834 (Encyclopædia Britannica 2018a). Peltier effect works like presented in the picture 4: a direct current is fed into a unit which has two different types of semiconductors. Depending on the type of semiconductors and direction of the current, heat is transferred from one side to another, cooling one side at the expense of heating the other. This transfer can be inverted by changing the direction of the electric current, with power depending on the strength of the electric current. (Brown et al. 2010.)



Picture 4. Peltier element’s structure (Adcol Electronics (Guangzhou) Co 2019)

Benefits of the Peltier element are the lack of moving parts and smaller size compared to previous methods. The element is also quiet compared to compressors and doesn’t employ harmful chemicals, eliminating the risks of leaks. Because of these reasons it is popular in travel fridges, where these benefits turn to requirements. It can also be wielded in heating for even better effect due to its own energy losses. It can also be made to follow the shapes of the cooled object to optimize the use of space.

Its greatest weakness is low power which greatly limits its use in large or very cold applications. It also has a high price tag which further limits its uses to special applications, where compressors and absorption are impractical. As such it is rarely utilized in real estate, individual home electronics not included. (Tellurex 2010.) Main goals in R&D are to improve the coefficient of performance and efficiency with new materials and thin film technology, but nothing revolutionary can be expected without completely new knowledge about thermoelectric phenomena (RTI International S.a).

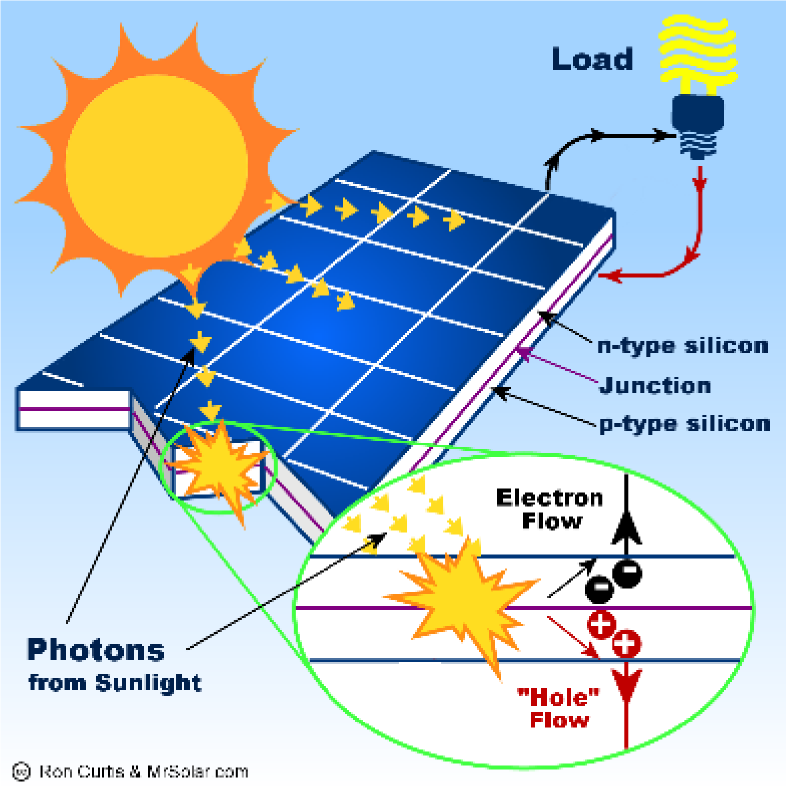
3 ELECTRIC COOLING

Renewable energy refers to energy sources that aren't based on the use of fossil fuels. These include solar, biomass, geothermal energy, tides, waves, wind and hydro power. The biomass part of recycled fuels is also included under this category, under biomass. (Uusiutuva energia 2018.) As the most cooling works either with electricity or heat, it is logical to handle the suitability of renewable energy for refrigeration using this division.

Cooling is easy to achieve with electricity. Renewable sources are employed to produce electricity which powers a cooler. This makes it possible to use renewable energy in everything that needs power alongside cooling. If there is no demand, electricity can be stored into batteries or sold, increasing the benefits of the system. The biggest weakness is the need for reliable electric grid, as blackouts affect the system immediately. Other weakness is the inability to use low temperature heat energy which can be gained from multiple sources, system itself included.

3.1 Photovoltaic cooling

Photovoltaics means producing power from solar radiation using solar cells (Komp R 2016). This happens due to the photovoltaic phenomenon, described by Albert Einstein. This gave him the Nobel prize in physics in 1921. (Encyclopædia Britannica 2018b.) Most photovoltaic panels based on this phenomenon are made from silicon dosed with boron and phosphorus. (AZoOptics 2008.) When this kind of a cell (picture 5) is under sunlight, photons separate from atoms. These electrons travel to the cells negative n-side, through the circuit, and to the cell's positive p-side. This cycle continues if photons hit the cell. A second less common method utilizes solar energy by a concentrating mirror and a sterling engine -operated generator. A system like this has the efficiency of a good solar panel, but as a significantly more expensive and mechanically more demanding it hasn't become popular (Savolainen S.a.).



Picture 5. Solar panel's operation (MrSolar.com S.a)

Photovoltaics operated cooling doesn't differ from the classical use of solar panels as technology is the same. The largest differences are in momentary power demand, caused by the start-ups of electric motors and longer time periods at peak power in high temperatures. These can be covered with large enough power output and storing capacity, such as a large number of panels or batteries. Refrigeration can also be adjusted and timed, like by bringing the temperature lower during daytime and letting it rise during the night when energy is not available.

The system is simple and can be connected to an existing electric system relatively quickly, if there is no need for large changes, for example for replacing all the cables or electrical cabinet (Beaudet 2018). It can be used both as a main source of electricity and an alternative for commercial power. It is also possible to apply it as backup power if investments are made to improve reliability and self-reliance. In this regard it is beneficial that solar panels are very durable, most panels can reach 25 years of age when 80% of the original power output is used as a measure. (Maehlum 2012). The final positive aspect is that electricity has more possible applications if cooling is not required.

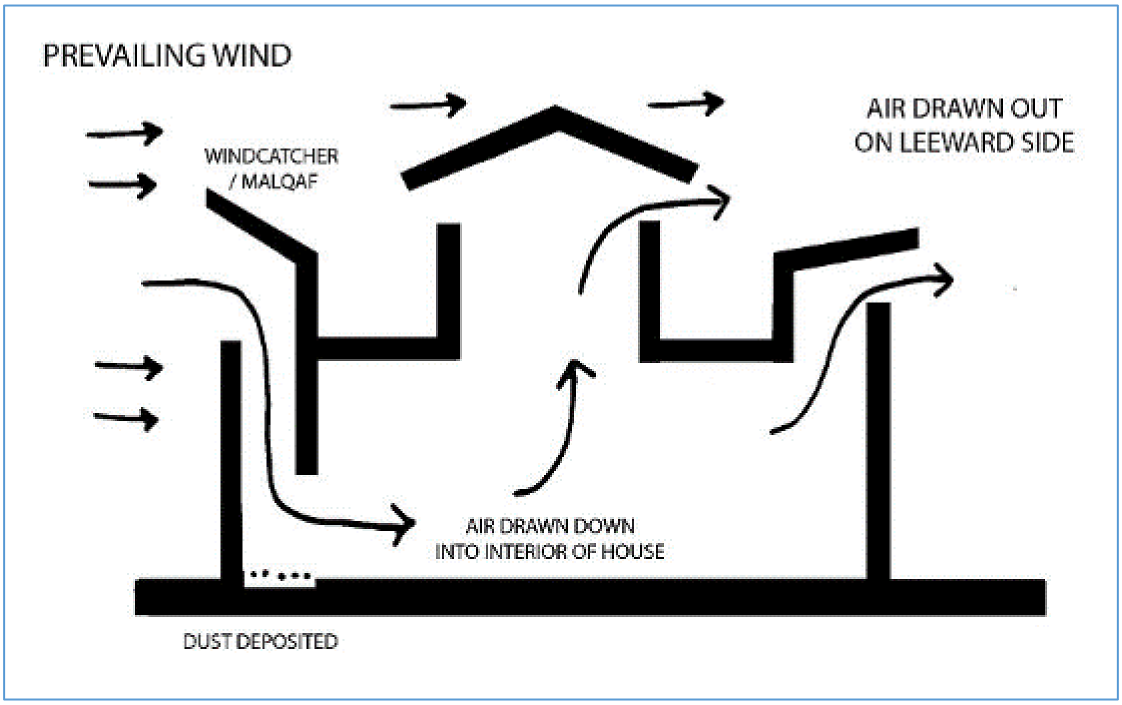
Photovoltaics Achilles' heel is its availability only during the daytime. Demand for cooling is lower at night, but uninterrupted supply requires a large battery capacity and power to charge it alongside daytime refrigeration. Long gaps or insufficient charging power can and will interrupt it if batteries run out. Batteries also suffer from shortened lifetimes in constant use, as charge and discharge cycles take place continuously, and large portions of their capacity are depleted (Power-Thru 2016).

3.2 Wind and wave cooling

Wind power comes from the kinetic energy of wind. This source of energy has been used hundreds of years for pumping water to milling grains and from the 1990s onward more and more in electric production. (Pimiä et al. 2014, 10.) Despite of different turbine types and technologies, the principle is always the same: A rotor is moved by the wind and it transforms wind’s kinetic energy to mechanical energy. Like in the modern turbines of the picture 6, this mechanical energy turns a generator which produces electricity. Some of the advantages include around the clock production, higher power output than photovoltaics and smaller emissions compared to manufacturing of solar cells (Redlitz 2016). In many applications it is best to combine wind with solar energy, especially in smaller ones.

Picture 6. Current industry-standard wind turbine (Monconduit 2018)

One of the challenges wind turbine encounters is the turbulence which reduce the power. From this reason, turbines are placed somewhere where air currents aren't affected by it. These places should also be as high as possible to reduce the turbulence even further and improve power due to faster winds. If placed on top of buildings, resonations caused by the turbine must be considered, as buildings can amplify these. (Boxwell 2017.) For now, wind is not suitable for cooling in a significant scale. The most common method is a windcatcher like in the picture 7, meant to guide winds into buildings to create a chilling breeze. When combined with evaporation of water, this old architectural solution is still useful when heat pumps aren't practical for one reason or another. (Roaf 2005.) It could also support other methods, for example improving the air flow around heat pumps condensers.



Picture 7. Wind catcher's basis (Fellanamedlime 2010)

Wave power could be regarded as a subcategory of wind energy, because it changes movement of air to movement of water. The idea is to collect and exploit the kinetic energy stored in waves to produce electricity. This is a rather new form of renewable energy and for that reason it is still under development. One of the possible systems is the one in the picture 8 which floats on water and uses hydraulic cylinders to rotate a generator and produce (Greenpeace UK 2008). The potential of this form of energy is estimated to be significant: In the USA alone 66% of consumed electricity could be made using only the waves within its own shores (U.S. Energy Information Administration 2018). Like wind, it can’t be utilized directly to cool and is limited to shores with predictable and strong winds to be a practical form of energy. There are also technical issues that slow down development, like the amount of stress a system experiences during storms. (Letcher 2014.)

Picture 8. Pelamis P2 wave power system (Pelamis Wave Power 2011.)

3.3 Hydro and tidal cooling

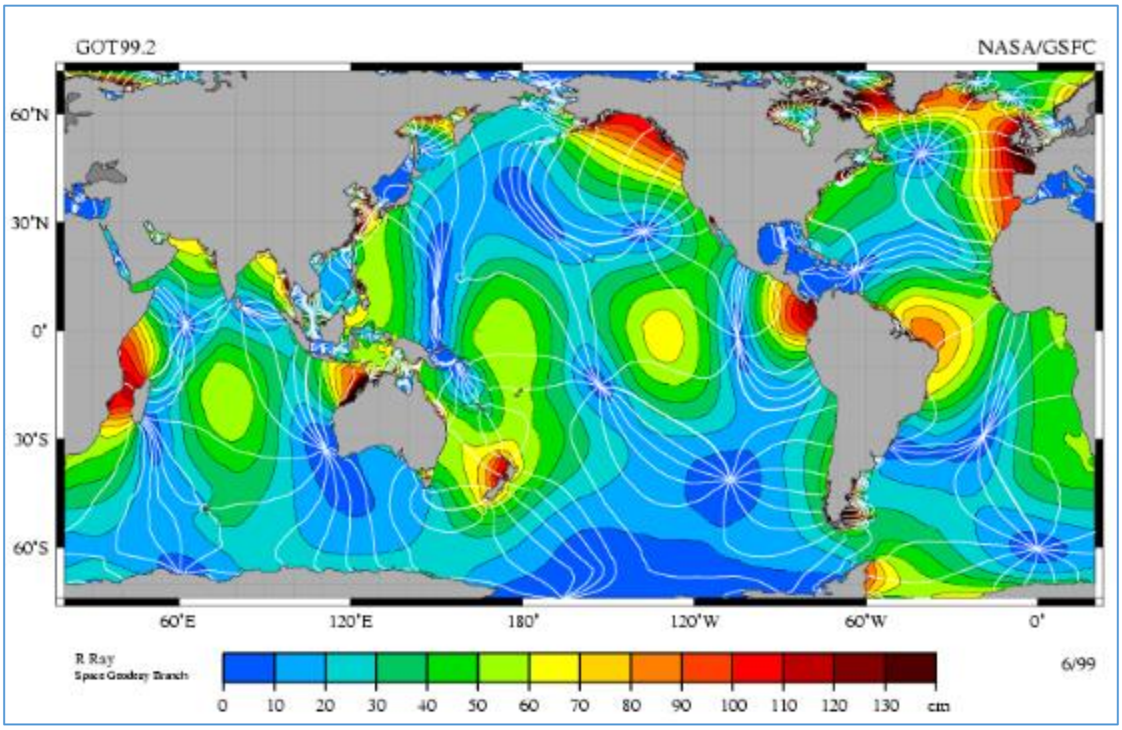
One of the oldest energy sources alongside wind, hydropower gains its force from movement of water. Rotating either a waterwheel or water turbine, waters’ kinetic energy is turned to electricity. The largest uses are in power generation where it acts as an adjusting power and covers peak demand (Energiateollisuus 2018). Its significance is expected to increase as other sources of renewable energy grow, due to hydropower being now the only economically viable way of storing energy in a large scale thanks to pump power plants. (KEMA Consulting Gmbh 2015).

Hydropower doesn’t create carbon dioxide emissions and is very reliable. Only long rainless seasons can affect the flow of rivers and therefore reduce power.

As an investment, hydropower is an expensive one but this is counteracted by being also one of the most enduring. Finland's oldest hydropower plant, Vanhakaupunki hydropower plant in Helsinki, was built in 1876 and is still in use. (Helen Oy 2017). Hydropower can produce plenty of energy if the flowrate or height of the fall is substantial. In China, the Three gorges dam for example can produce 8300 megawatts of power, due to its 110-meter fall and around 10000 cubic meter flow (Mäkeläinen 2016).

Hydropower is however very restricted by geography, as the number of suitable placements is limited. Most rivers and rapids in Finland are already used for generation of power and the remaining ones are either too small for investments or protected under nature conservation laws. Existing plants can't be upgraded to higher power output using current technology. (Energiateollisuus S.a.) Globally hydropower has some unused potential, if western countries are ignored, but there is no agreement on how much potential there is. Some of this potential is also difficult or unsustainable to build or operate due to economical or technical challenges. Environmental, social, politics and economy also put restrictions on what potential can be even considered. (World Energy Council 2010).

Tide based power is gained from Moon's gravity. This form of hydropower is further in development than wave power (Cunningham 2014) but is new if wind or biomass are used as measures (Rutledge et al. 2011). Production estimates are high, but only in shores that fill specific conditions, limiting is availability. According to NASA (Picture 9), many shorelines are insufficient for tidal power, so it won't play a large part on global energy production. Tides are also on their own schedule, so if production and consumption don't match, a large amount adjusting and storing capacity is needed (Student Energy 2015). Solving these issues is slow as research doesn't receive enough funding for development and testing. This is caused by environmental concerns and legal questions regarding ownership of underwater land. The economic risks are too high for substantial sums. (Rutledge et al. 2011.) For these reasons tidal power won't become a significant energy source for years. An unfortunate outcome, as its advantages and disadvantages are comparable to traditional hydropower.



Picture 9. Change of tides in centimetres, darker areas better (NASA 2019)

3.4 Electric biomass cooling

Production of electricity or heat using biomass in electric or CHP power plants which use following fuels:

- biomass grown as a fuel, such as reed canary grass and palm oil
- industrial and agricultural residues, such as sawdust and surplus dough in bakeries
- fuel generated from industrial, agricultural and residential bio waste, for example landfill gas
- wood-based fuels for forest industry processes. (Bioenergianeuvoja 2018; Bioenergian käyttö 2018.)

Processes are the same as any normal coal, oil, or natural gas burning power plant uses to create electricity. Biggest differences are in the insertion of fuel and emission control, due to chemistry and varying forms of the fuel from landfill gas to wood chips. Biomass is the most common source of energy for forest industries as sulphate pulp mills consume nearly half of the wood mass they receive as energy. This is the reason why biomass is a significant form of energy in Finland, because around 80% of all biomass energy is generated in forest industries. (Suomi on bioenergian suurvalta 2007.)

Using biomass for electricity and further for refrigeration is easily predictable compared to solar and wind energy, as their production doesn't not depend on weather. Energy can also be stored for periods of time that only depend on the demand and size of the storage. Some processes offer plenty of fuels as a side product, like pellets created from sawmills which helps the overall economy of these processes. A wide selection of fuels ensures the availability of energy and boilers capable of using many fuels can choose the cheapest fuel in each situation, reducing costs. In terms of climate politics biomass is considered for now as a zero-sum game, as biomass takes carbon dioxide from the atmosphere during growth. In Finland biofuels also have governmental support due to their significant effect on employment and tax revenue.

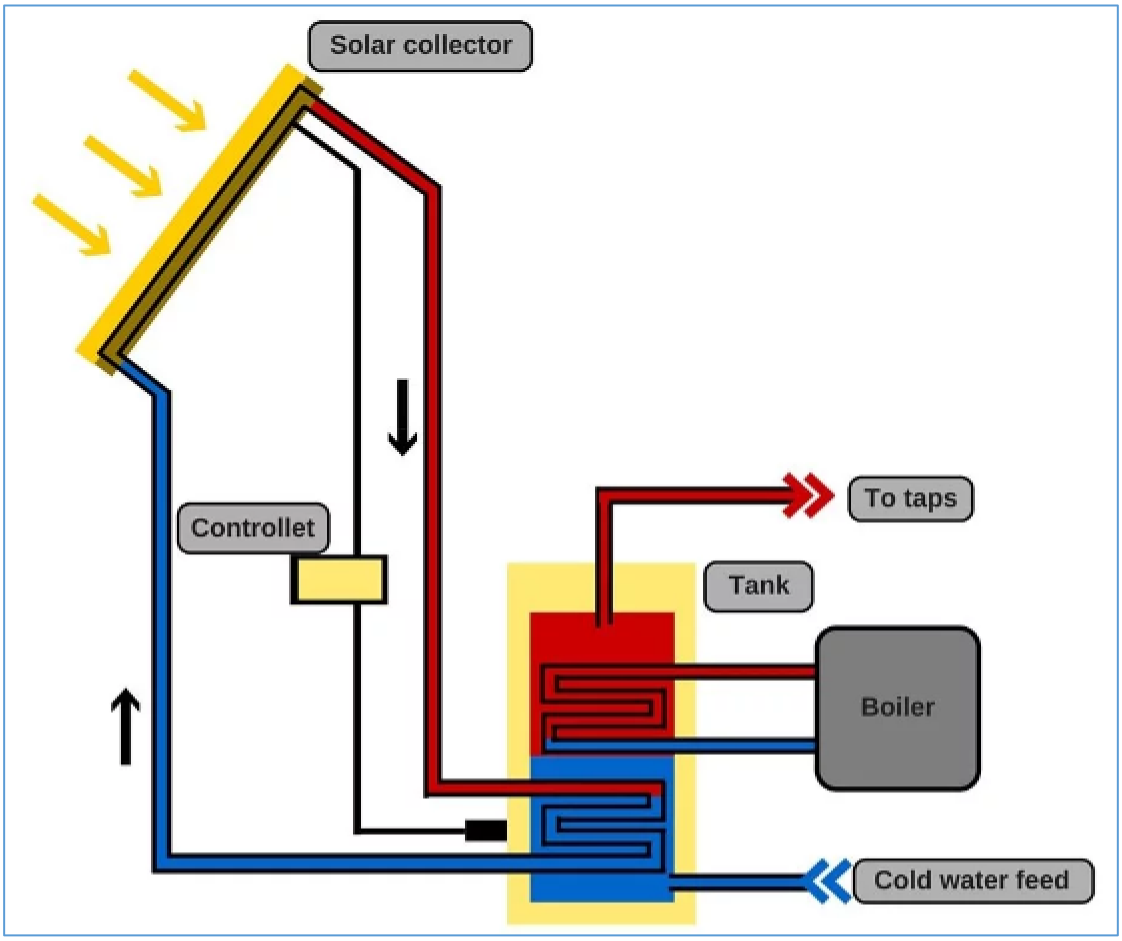
Some weaknesses biomasses have is the dependence on efficient logistics. As the price of transportation rises, so will the price of biomass, even if it was originally free. Biomass also has a lower energy density than fossil fuels, reducing the effectiveness of transporting (Suopajärvi 2013). After certain distance there is no more point of buying biomass, making biomass a very local source of energy. Since transferring electricity is easy by wires and cables, this is not a deal breaker, but energy is lost anyway. For reasons of cost-effectiveness the biomass needs to have a lower cost than fossil fuels due to increased need of maintenance and technical challenges. The need for these heavy investments prevents individuals from producing power for domestic purposes. As such only established power companies have a shot to produce electricity from biomass with economic success.

4 HEAT BASED COOLING

Methods where refrigeration happens with heat operate mostly using an absorption system. Heat energy is used directly for cooling without intermediate phases which improves overall efficiency over electric based methods.

4.1 Solar heat-based cooling

Solar collectors refer in this work to systems that collect, store and utilize the Sun's heat including passive methods. In solar collectors the heat from the Sun warms water or water/glycol-mixture circulating in the system by a pump or passively due to heat expansion. The heated liquid is then directed into a tank for later use, or a coil that heats the water being used. A collector like this or in the picture 10 can be connected to other heating solutions by changing the boiler to any other method of heating.



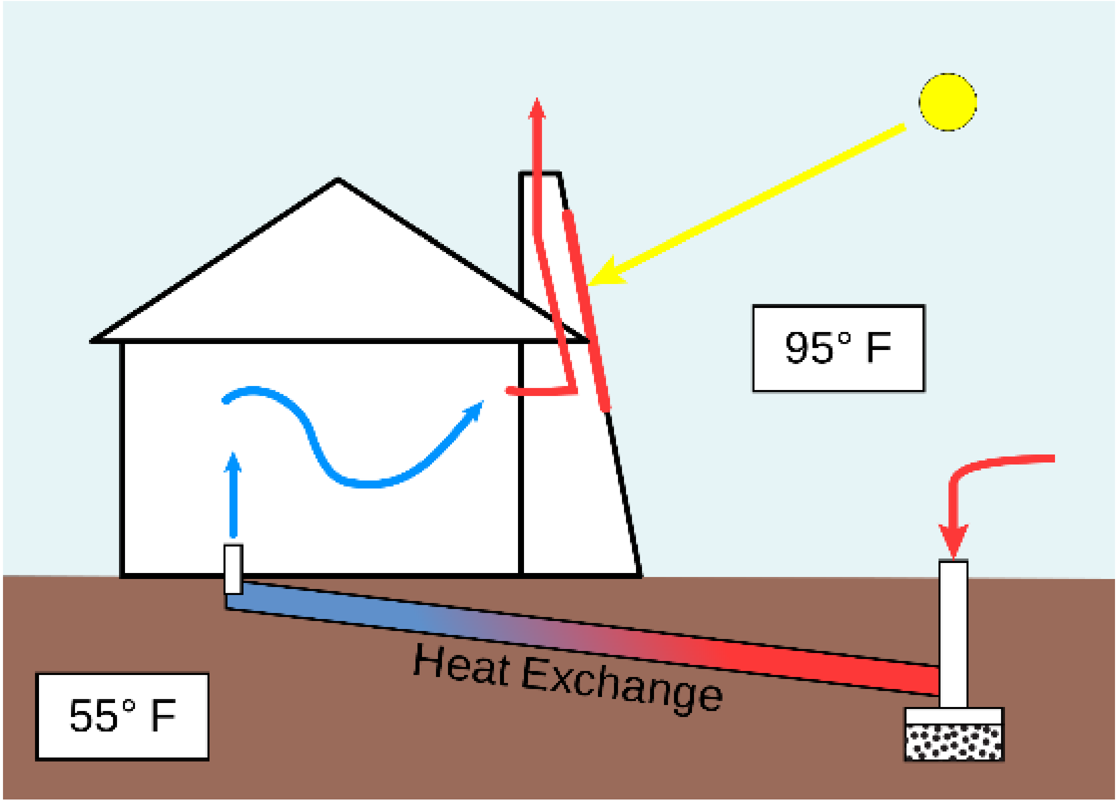
Picture 10. Solar heating method (Science ABC 2016)

In many commercial solar power plants, such as in the picture 11, solar radiation is concentrated to one spot by mirrors, rising the temperature to hundreds of degrees depending on the total surface area of the mirrors. In this spot a boiler, a heat exchanger or a pipe transfers the heat to a liquid, water in most cases. This heat energy is turned to usable energy with the same technique as in an everyday coal plant or used as-is heat. Some variations produce extra heat for storage and later night-time consumption. A plant like this operates around the clock improving availability of energy and cost effectiveness.

Picture 11. Concentrating solar power plant (Bureau of land management 2015.)

The heat energy gained by solar collectors can’t be used directly to cool anything but can power an absorption cooler or electric production in concentrating solar power (CSP). However, systems like these are complicated and therefore employed rarely. With photovoltaics the system consists of just a heat pump and photovoltaics themselves, while solar collectors need three separate flows, possible backup, multiple pumps and a cold sink. It does have the benefit of being suitable for creating a baseline for cooling and the possibility of making even half of the refrigeration required. (Eicker 2012.)

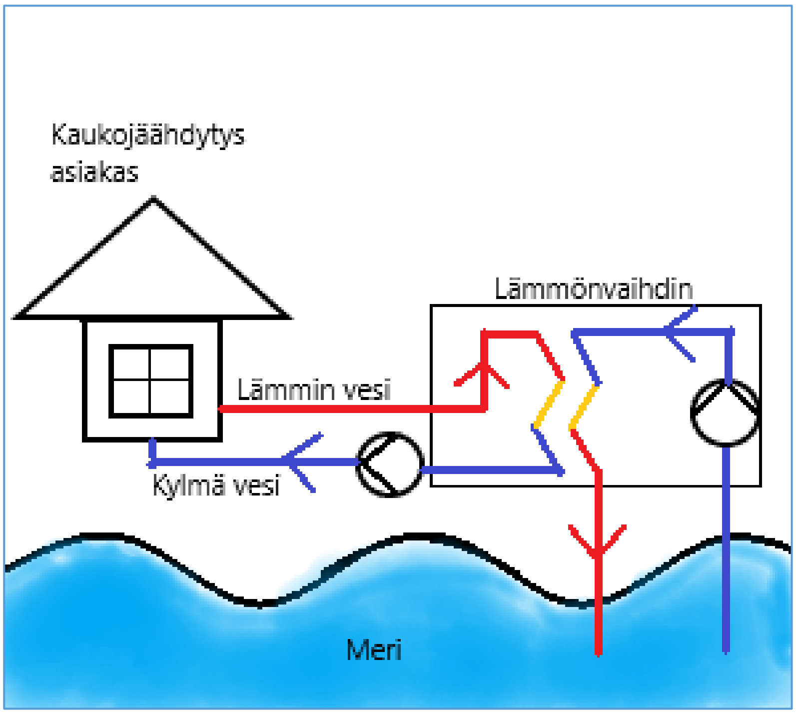
A second method is a solar chimney, one of which shown in the picture 12. This architectural solution is powered by a chimney heated by the Sun and where warm air rises, cooler air inside the building flows to replace it and therefore creates a chilling breeze (Hanania et al. 2017). If the temperature of the outside air is high, the airflow must be significant to provide any cooling. To reach this the chimney must be sufficient in size. (Szikra S.a.) The resulting breeze can interfere the comfort of the building and prevents its utilization in buildings that demand strict control of airflows. For instance, in operating rooms the solar chimney can’t be used as air must be replaced up to twenty times every hour. Coupled with quality requirements for moisture and cleanness air condition becomes the most practical method. (Roy & Stevens 2018.) Solar chimneys are efficient utilization of energy though, as their power comes from the Sun without machinery and power is proportional to how much heat the Sun gives.



Picture 12. Operation of solar chimney, temperatures 95°F=35°C and 55°F=13°C (Hanania et al. 2017)

4.2 Free cooling

The idea behind free cooling is to use the colder air or water outside the building directly for refrigeration as shown in the picture 13. Unlike traditional heat pump-based air conditioning, free cooling doesn't need energy to actively transfer heat out of the building instead of letting it flow naturally on its own to cooler medium. Energy is only required to operate pumps or fans that move air or coolant through the system. This principle remains the same regardless of size or power and can be used anytime when cooled object is in a higher temperature than it is meant to be with a heatsink being below 10 degrees Celsius. (Toivanen 2010.)



Picture 13. Idea of free cooling (kylmä=cold, lämmin=hot, meri=sea, vesi=water, lämmönvaihdin=heat exchanger, kaukojäähdytys asiakas=district cooling client)

Datacenters are a prominent example of using free cooling. As servers consume a lot of energy, they also create large amounts of waste heat. Mechanical refrigeration is possible but would rise the energy consumption to unsustainable levels in terms of economy. Using outside air directly is not possible, as despite of their weight and size, servers are delicate devices that can't be placed under the effects of the environment. Free cooling allows heat removal without endangering the center to the elements. The amount of waste heat makes datacenters often a significant producer of heat which can be used by connecting the center to a district heating network to reuse the energy. (Selvitys IT-ympäristön… 2010.)

Free cooling is simple to build and therefore easy to apply alongside other methods of refrigeration as a main system or an auxiliary one. Reasons behind the use of free cooling are related to the low cost of operation which makes it common in commercial applications like in industries. The size of applications can be anything from individual buildings to entire cities. It is also friendly to the environment as there is little need for chemicals and the risk of leaks is small. (Marjala 2015.)

A major downside is the requirement of significant difference between temperatures of the environment and the cooled object. This difference is at its smallest when the demand is at its peak. During the cold season the potential is at its peak, but demand is low. Free cooling also becomes very inefficient when outside temperatures go above ten degrees Celsius. As such it is suitable for refrigeration in Finland, as annual average temperatures remain below six degrees Celsius (Ilmatieteen laitos 2018). The continuing climate change can however make this advantage smaller than expected.

4.3 Geothermal energy and heating for cooling

This is the use of the grounds heat which is either created by geologic phenomenon or is stored heat from the Sun. In most real estate's it is based on a heat pump, collecting heat from grounds by a compressor system. (Wahlres Oy S.a.) In electric power generation it is utilized with power plant processes that exploit the heat of hot springs to rotate a turbine, either by steam or by a working gas (Renewable energy world S.a.). The use of geothermal energy by building underground won't be researched in this work, as it belongs under low energy building and construction.

In areas where geothermal energy is plentiful, it can produce large sections of the energy need. In Iceland geothermal energy covers over 90% of heating of buildings and one fourth of consumed electricity (Promote Island 2014). The reliability and availability of geothermal energy help in these as they don't depend on weather patterns, only on the depth the energy is gained from and technology that is used. The systems themselves are durable and reliable, needing less maintenance. Also, it is also good in terms of energy efficiency and utilization of space (GreenMatch 2014.)

Unfortunately, this renewable energy can only be used in volcanic areas which of most are placed around the Pacific Ocean, where geothermal energy is closer to surface. Iceland is a rare exception to this rule. (Luhr 2003.) In other parts of the world, like in Finland, use of this energy source requires drilling many kilometres underground, because temperatures are too low near the surface. Regardless of depth this causes an earthquake risk which turned to reality in Basel, Switzerland, causing around seven million Switzerland francs

(6.3 million euros) worth of damages and slowed down similar projects elsewhere (Geosto Oy S.a.; Valuuttalaskuri.org 2019). It is neither an emission-free source of energy, as small amounts of methane and ammonia can rise from the drilled holes, both classified as greenhouse gases. It also can't be harvested indefinitely from the same spot, as the cooling bedrock reduces production and at worst turns the area useless for later production. Other issues include the high cost of investment and limitations on land usage, like how close to other plants and underground infrastructure geothermal energy can be build. (GreenMatch 2014.)

Geothermal heating that uses significantly lower temperature heat stored in the surface level ground and bodies of water is a lot easier to utilize around the globe. It can be also employed in cooling by pumping heat into the well, where it can be pumped up later. In this case geothermal heating works as a storage, with the size being limited only by the properties of the bedrock or ground instead of volume. (Arola 2018)

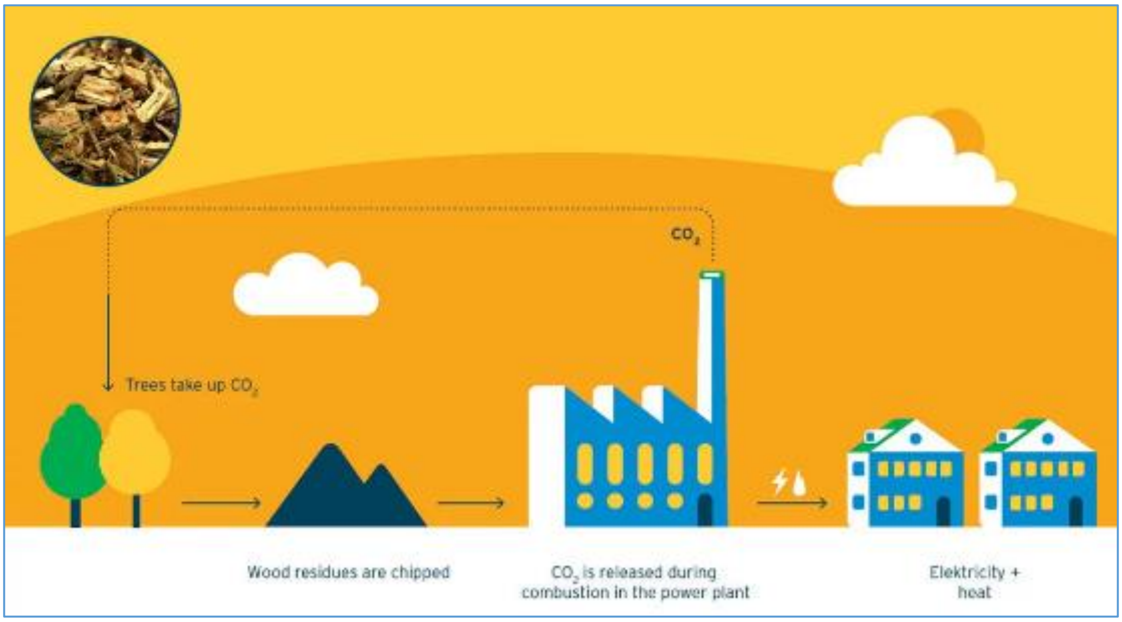
4.4 Thermal biomass cooling

Production of electricity or heat using biomass in condensing and CHP power plants which uses one of the following fuels:

- biomass that's grown as a fuel, such as reed canary grass and palm oil
- industrial and agricultural residues, as in sawdust and surplus dough in bakeries
- fuel generated from industrial, agricultural and residential bio waste, for example landfill gas
- wood-based fuels for forest industry processes. (Bioenergianeuvoja 2018; Bioenergian käyttö 2018.)

Process is identical to burning coal, oil or natural gas in a normal power plant. Biggest differences can be found in fuel insertion and control of emissions due to chemistry, and whether the fuel is gas, chips or other form. The most common method is to burn biomass in a boiler that provides heat to an absorption refrigerator which is the main source of cooling.

The large selection of fuels is positive for this method, as fuel can be anything from energy wood, old flour or bio waste, if the biomass is suitable for the process. The ease of storing the fuel is another positive thing, as it helps to even out the difference between production and demand, both in short and long term. If needed, heat can be stored in a way that is easier and less costly in a large scale that storing electricity. In case of flora there is also the benefit of carbon cycle shown in the picture 14, where carbon released during burning gets bound to biomass. This is often the main argument behind the idea where biomass and especially wood are treated like they don’t produce carbon dioxide. (Biomassavoimala 2017.) Heat based cooling doesn’t have to worry about requirements like electricity has to, clean and temperature-controlled burning is enough.



Picture 14. Carbon cycle, the argument for zero emissions (Biomassavoimala 2017)

Although biomass is wielded a lot to make electricity, heat and process steam, in refrigeration it is used mostly in Europe’s large-scale district cooling networks, as small systems suitable for domestic applications don’t exist on the market (Sulzbacher & Rathbauer 2011). This is in line with Agricultural Utilization Research Institutes analysis in chapter 5.2. (AURI 2016). Unlike fossil fuels, biomass has a time limit in storage, after which its quality drops due to biological decomposition (Suopajärvi 2013). Burning the biomass also creates large amounts of heat which usefulness depends on its temperature. Usually this temperature is too low to be used for anything else than heating buildings and water. If this heat isn’t needed, it must be removed from the system anyway to ensure processes can continue. This leads to losing energy into the air or bodies of water.

5 COOLING APPLICATIONS WITH RENEWABLES

Although renewable energy has the capability to slow down climate change and replace fossil fuels. From a business perspective being environmentally friendly alone won’t suffice as a reason for sometimes very high costs of investment. If an investment doesn’t bring any profits, cost reductions, lower risks or bring more customers that investment is pointless from the business point of view. A reputation as a company that takes environmental concerns seriously won’t help in bankruptcy. An investment without supportive examples or numbers to show is even worse.

From this reason, there is a need to provide examples that show renewable energy’s potential in cooling and the economic benefits it gives. The example about logistics centre demonstrates how a single building can benefit from the use of renewable energy as a way of reducing financial risks and as a statement of the company’s responsibility to the environment. Pinecrest shows the economic gains which renewables can give compared to fossil energy sources.

5.1 Logistics centre of S Group

Because power doesn’t differ based on its source, it makes sense to treat photovoltaics as a replacement for grid electricity and compare them in cooling. Inex Partners logistics centre in Sipoo which was completed in the fall of last year, is used in this example. S Group’s annual report from 2017 states that the centre “sucked 28740 megawatt hours of electricity”. Around 60% of this, 17244 MWh, came from renewables mainly in a form wind energy. Using these values, it is possible to calculate what would happen, if all the energy the sun radiates on the centres whole roof area is used for refrigeration.

The following numbers are used as default values:

- Solar constant is 1000 W/m^2.

- The centres whole roof area (144000 m^2) is available.
- The available radiation energy is 900 kWh/m^2 per year.
- The centres certified output powers, 11.1 MW for refrigerator section and 3.3 MW for freezer, are maximum power outputs.
- Weather conditions are assumed to be good for solar energy production. (Perälä 2017; Manninen 2017; Virtanen 2013.)

Table 1. Photovoltaic system technical data (Amerisolar 2016; SolarXon 2012; Astronergy 2017.)

	SolarXon ES-140P	Amerisolar AS-6P30	Astronergy STAVE 2	
Electricity consumption	28 740			MWh
Renewables part of electricity	60 %			%
Renewable energy before installation	17244			MWh
Emission factor	164			Kg/MWh
Emissions before	1885344			Kg/a
Panel length	1486	1640	1648	mm
Panel width	676	992	990	mm
Peak power (STC)	140	275	290	W
Module efficiency	13.9%	16.9%	17.8%	%
Module surface area	1.005	1.627	1.632	m2
Panels for area	143350	88513	88261	Pcs.
Power	20	24	26	MW
Energy	18014	21902	23069	MWh
Renewable energy after installation	35258	39146	40313	MWh
Excess electricity	6518	10406	11573	MWh
Consumption coverage	139	169	178	%
After transformer (75% efficiency)	105	127	133	%

Emission reductions elsewhere	1069018	1706650	1897939	Kg/a
Emission reductions total	2954362	3591994	3783283	Kg/a

When built with these panels, the photovoltaic system could provide all the cooling the centre needs around one and a half times (1.39-1.78), enough to cover losses in the transformer and the cables. Calculated values for annual energy production are enough to cover the centre's whole electricity consumption and even leaves extra. If this energy is used elsewhere, like in a retail store, the carbon footprint can shrink nearly 1900 tons per year there. The total savings on emissions can be up to 3800 tons per year assuming that energy isn't stored for later use in the centre (CO2-päästökertoimet 2019).

The connection between the efficiency and surface area was calculated out of curiosity. In this calculation the hypothesis was that with better efficiency the smallest SolarXons panel can produce as much energy and power as the larger Astronergys panel. Because the Sun's power output won't change, it should be the only thing with any effect on gained power and energy. In the table 2 the calculations are the same as in table 1, but SolarXons panels efficiency has been changed to equal Astronergys panel.

The numbers were checked using the European commission funded Photovoltaic Geographical Information System. The peak power was set to 20 MW, losses at 14% and panel orientation was given to program to optimize. The results shown in both tables are near the values the program calculated, so the results are realistic and usable for evaluating the benefits and the effect of efficiency. (Photovoltaic geographical information system 2019.)

Table 2. Effect of panel efficiency. (SolarXon 2012; Astronergy 2017.)

	SolarXon ES-140P	Upgraded SolarXon	
Electricity consumption	28740		MWh
Renewable part of electricity	60%		%
Renewable electricity before installation	17244		MWh

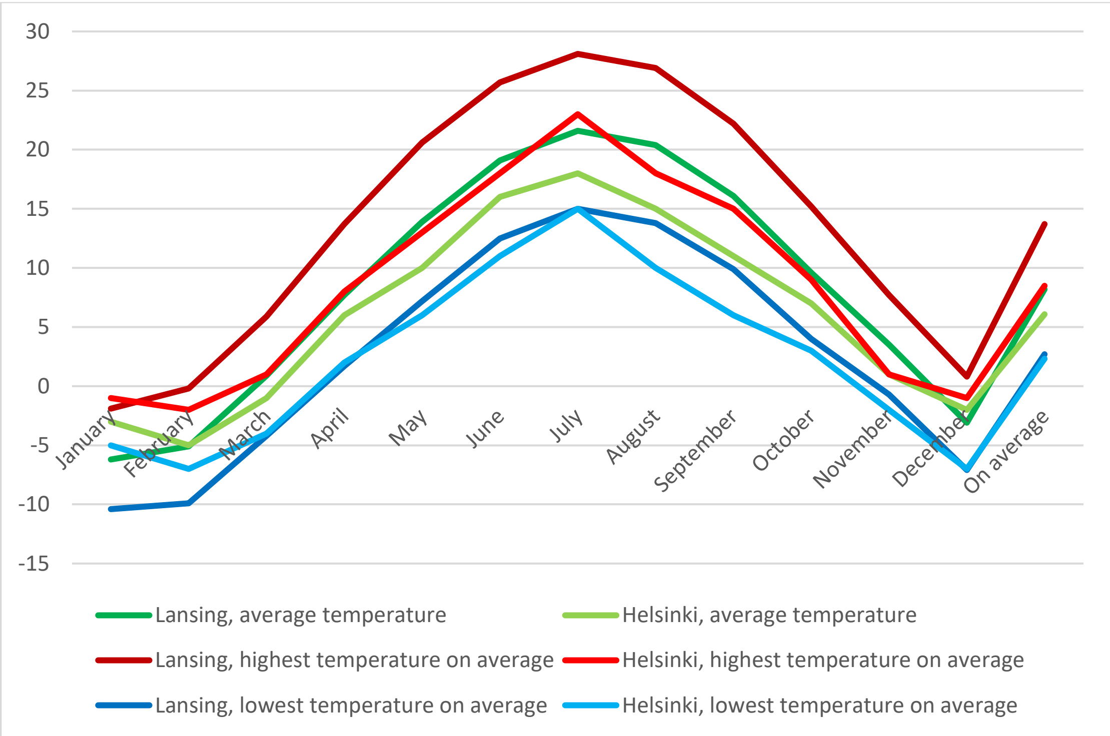
Emission factor	164		Kg/MWh
Emissions before	1885344		Kg/a
Length	1486		mm
Width	676		mm
Peak power (STC)	140	178	W
Module efficiency	13.9%	17.8%	%
Module surface area	1.005		m^2
Panels for area	143 350		Pcs.
Power	20	26	MW
Energy	18014	23069	MWh
Renewable energy after installation	35258	40313	MWh
Excess electricity	6518	11573	MWh
Consumption coverage	139	177	%
After transformer (75% efficiency)	105	133	%
Emission reduction elsewhere	1069018	1897939	Kg/a
Emission reduction total	2954362	3783283	Kg/a

These calculations show that better efficiency is the main reason why Astronergys panels creates more power and energy, resulting a greater gain than the number of panels, size or power can provide. Therefore, the hypothesis is correct. This is possible because it affects both power and produced energy per area, while the size only affects the area of collection. Power is dependent on size and efficiency, the number of panels is limited only by available space and how much funding is available. That is why it's better to invest on panels with higher efficiency than with size or power (Aggarwal 2019).

Logistics centre is also a major user of geothermal heat, gaining 20% of all energy needed from it. If the number sounds small, it is due to the sheer space of the building, equivalent of over 30 Finnish Parliament buildings, and annual energy demand of around 3000 detached houses. (S-ryhmän vuosi ja vastuullisuus 2018.) This value is cut by the timeframe in 2017 when refrigerator and freezer parts of the centre were under construction and the waste heat produced by these units is missing. The logistics centre is meant to utilize bedrock as energy storage for cooling in summer and heating in winter. (Logistiikkakeskuksen… 2010).

5.2 Pinecrest Medical Care Facility

Located in Powers, Michigan, the Pinecrest Medical Care Facility specialises in long term care, Alzheimer patients and rehabilitating therapy. The facility participated in 2016 to a project run by Agricultural Utilization Research Institute (AURI) in which University of Minnesota, Center for Urban and Regional Affairs (CURA) wrote a guide about using biomass for refrigeration. In the picture 15 the temperatures show that the location is a good analogy when researching cooling in Finland with risen temperatures. Temperatures in Michigan are on average higher than in Finland today except in wintertime when they are similar.



Picture 15. Average temperatures in capitals of Finland and Michigan (Climate-zone.com 2019)

All information about Pinecrest Medical Care Facility is based on published data of AURI (2016) and Cook (2015). This around 15800 square meter and four building real estate has burned wood chips in its heating from 1984 onward and updated the heating system in 2001 to make cooling possible with the same fuel. The cooling system uses a lithium bromide-based absorption machine that lowers the temperature of the circulating saltwater to 5.6 degrees Celsius. The necessary heat energy comes from a wood chip burning boiler. Waste heat is directed to a cooling tower where the heat is transferred to outside air with the evaporating water. Natural gas is employed as a backup fuel which is burned in two separate boilers. In addition, there exists a 10-kilowatt solar panel system that is left outside the analysis. The goal of the update was to save on fuel due to lower costs of wood chips that were around a third of natural gases per kilowatt hour at the time of the research.

In an economic sense this investment was a success: the system itself had a cost of 152 400 USD with piping and installation costing 173 391 USD for a total of 325 890 USD. On the rate of 4.9.19 the system would have a cost of around 135 200 €, piping and installation around 153 800 € and total sum of nearly 289 000 € (Valuuttalaskuri.org 2019). This sum was covered with a loan that was paid back in three to four years thanks to lower fuel costs. Fuel is consumed at a rate of 2800 tons per year for an annual cost 120 000 USD. This has become 10 000 USD cheaper a month than natural gas in 2014. Some of the negatives include twice the need of maintenance compared to natural gas or oil and a need for ash removal. Expenses of using biomass, such as cost of chancing grates, repairs of hydraulic systems and masonry of the boiler are not mentioned in the sources. This could indicate that these costs have already been noted, meaning that the previous values are net savings.

5.3 Feasibility comparison

Based on the comparison of benefits and disadvantages, using renewables both as a source of energy and a source of cooling are very similar. In the case of solar energy, the lack of emissions is a positive in both energy production and as a power source for refrigeration while biomass is an impractical source for both uses in small applications. Properties like these are so many that the information in the table 3 can be employed directly in the table 4 that shows their utilization in refrigeration. Photovoltaics for example need batteries for night time demand regardless of power use.

If renewables are only utilized in cooling, their properties must be considered. This makes it possible to compensate disadvantages and maximize benefits as much as possible, making the system beneficial both economically and environmentally. Considering the properties shown in the table 4 it is possible to achieve the set goals in refrigeration using the same principles. These tables also work as a demonstration why there is a need to collect information from multiple sources and use all available information. These numbers gained as an energy source aren't enough when designing a cooling system.

Table 3. Benefits and disadvantages of renewables as energy sources

Energy source	Benefits	Drawbacks
Photovoltaics	Available everywhere Quick to build No emissions	Available only during daytime Needs batteries for the night Requires space
Wind power	Quick to build No emissions	Power depends on wind Visually ugly and noisy
Wave-power	Great potential No emissions Available everywhere	Slow development Expensive Legal questions
Hydro-power	Reliable Economic adjusting power Negligible emissions Long term investment	Significant impact on environment Limited number of suitable sites Questions about water rights
Tidal power	Reliable No emissions Great potential	Can't be adjusted Limited number of suitable sites Slow development Expensive
Electric biomass	Wide selection of fuels Local Zero emissions	Unsuitable to small applications Large maintenance demand Fuel logistics
Solar heat	Available everywhere Quick to build No emissions	Unsuitable to small applications Large amounts of waste heat Needs electricity and space
Geothermal energy	Very reliable Negligible emissions	Expensive Risk of earthquakes

	Suitable for base production	Easy to acquire only in volcanic areas
Geothermal heat	Very reliable No emissions	Expensive Limitations in urban areas
Biomass heat	Wide selection of fuels Local Zero emissions	Demand for maintenance Fuel logistics

In terms of emissions renewables are rather similar, greatest emissions are made during manufacturing, decommissioning and transportation. Only a small amount is created during operation. Largest differences are in their disadvantages that can change from visual drawbacks and noise to need of transport and huge upfront costs. This is one explanation on why it is beneficial to combine different renewables together. Photovoltaics can be used in daytime only without batteries but combining them together with hydropower energy becomes a lot more available in night time. This kind of covering of weaknesses is important as cooling requires large amounts of energy.

If renewables are used only for refrigeration, benefits and disadvantages in the table 4 are important. Many forms of renewables can't be combined with an absorption refrigerator as they are mostly suited for power production. Electricity is too valuable to be consumed in absorption processes that create less cooling compared to compressor systems. Many sources are also overkill in price to be used only for refrigeration. Geothermal is suitable for covering the baseload but it needs a large consumer in a hot location, such as a district cooling network, to make any sense in investment costs.

The best way to implement cooling is to use at least two forms of renewables that have different weaknesses for the most part. Wind power and wave power both depend on wind, so they don't support each other. A hybrid of wind and biomass is much better, as wind works as an emission-free main source of power supported by biomass during a weak breeze. Even better results can be reached by combining three or more sources, if one works to store and adjust power. In refrigeration this can be done via creating large storages of hot and cold-water tanks that can balance production and consumption.

Table 4. Positives and negatives of renewables in cooling

Source	Strengths	Weaknesses
Photovoltaics	Electricity can be used elsewhere on demand Can be placed on roofs	Low efficiency Need of batteries and their maintenance Inventers wear down
Wind power	Power density on area of ground Can be placed on roofs	Unsuitable with absorption Resonation problem in buildings Supply and demand may not meet
Wave power	Can be fitted on shores of urban environments Power density on area of ground	Unsuitable with absorption Depends on wind
Hydropower	Reliable Easy to adjust Mechanically simple	Unsuitable with absorption Requires a running body of water Expensive
Tidal power	Good for baseline cooling Lots of power on a small area	Unsuitable with absorption Limited number of suitable areas
Electric biomass	Selection of fuels Easy to adjust	Complex process Expensive
Solar heat	Can be placed on roof Affordable Easier to store than electricity	Not suited to small applications Large amount of waste heat Requires power
Free cooling	Can be used in tandem with other methods	Heat is lost without reuse
Geothermal energy	Reliable Cost-effective in a long run Very suitable for heating	The well can cool down in long term use and difficulty of rising power output from designated

Geothermal heat	Independent from air temperature Suitable for heating	Suited mostly for heat storage Requires power
Biomass heat	Easy to adjust Storing of fuel	Fuel must be affordable, or cooling is done with waste heat

As the table 5 shows, not all forms of renewables are on the same page in terms of use. Solar, wind and geothermal energy don't have much significance in the energy sector as water and biomass have. This is because water and biomass have much more history behind them than solar, wind power and geothermal. They are however applied to refrigeration already, albeit indirectly by powering heat pumps. Solar heat is employed locally to cool industrial processes and real estates but not in the scale of district cooling grids. With biomass it is more about the size as these systems are too large, complicated and expensive for domestic applications. In commercial applications it is rather common. Wave power and tidal power are both still under development and are therefore unlikely to become commercially available for years, maybe decades. Hydropower can be used in cooling, but it is more efficient investment to utilize it in electricity production or for adjusting power.

Table 5. Use of renewables currently

	Use in cooling
Photovoltaics	Through grid or to own use
Wind power	Through grid, to own use in island operation only
Wave power	Under development
Hydropower	Through grid, to own use in island operation only
Tidal power	Under development
Electric biomass	Large and medium applications through grid or district cooling in CHP processes
Solar heat	Through grid, limited domestic use
Free cooling	As part of an existing process or district cooling
Geothermal energy	Through grid or absorption locally
Geothermal heat	Mostly in a form of heat storage

Biomass heat	Through grid or district cooling, only large businesses utilize for own use

6 SUMMARY

Using renewable energy for cooling is possible and economically viable option, as existing examples can demonstrate. Various methods are advanced and usable in challenging situations, where either environment or operation sets special terms. Solar, wind, hydro and biomass have achieved a point where they are financially viable options without the need of monetary backing. Control systems and automation are at a level where hybrid systems are practical and can bring more benefits to their users than each individual system. Foundations for sustainable solutions are provided already on the drawing board with material selections, details that improve efficiency and modular systems that can be easily upgraded as technology advances.

So far, the largest challenges are formed on the interfaces between refrigeration systems and renewable energy, where heat and electricity turn to cooling. Not all methods of refrigeration can be combined with all forms of renewables, limiting possible options. Biomass can be used as an energy source for cooling in a power plant but not in a detached house due to its price and complicity. Absorption coolers can run on almost any source of heat, but the low efficiency means the heat must come from waste heat or fuel with a very low cost. Otherwise the costs rise to unsustainable levels. As such the method of refrigeration must correspond to the used source of renewable energy to maximize the gained benefits.

A second major weakness is reliability and predictability, two largest challenges renewable energy has. These issues are small for biomass and hydropower but wind and solar require oversized production and storage capacity to eliminate interruptions in cooling. This places hydropower in a difficult position as it is expected to work both as adjusting power and baseline power like nuclear power today. In hospitals patient safety alone demands that backup systems are in place, increasing price of investments. Large cold storage halls can afford to have their temperature rise in a short run, but no amount of insulation is enough to prevent losses in a prolonged summer heat. Based on this backup systems and alternative fuels are needed if reliability is wanted. Hybrid solutions are therefore very likely to become commonplace.

Some solutions require concessions when designing a building and during construction, some can’t be used in specific circumstances at all. For instance, with biomasses one can end up using the more expensive fuel due to boiler limitations. The number of combinations is very high but almost all options have limitations and requirements that prevent some being employed for the same purpose. To create a cooling system that is useful, more calculations and research might be needed, as turnkey options might not be available. Many existing applications were created using products of different manufacturers that weren’t designed for that application. How many homeowners do have considered solar panels as a backup for their freezer and air conditioning when the power of those panels has been calculated?

According to these results the next goal in the utilization of renewables with cooling is to get these solutions to wider use and within the reach of an average consumer. This means engineers must work harder to find more affordable solutions, and politicians need to find the will to advance sustainable policies at the expense of financial interests. Not to mention the consumer who must learn to demand taking the environment into consideration in more things, cooling included.

Research and development for new and better answers go forward in material technologies as well as consumer habits and is creating visible effects under the canopies of waste collection points, statistics and street view. This thesis has contributed to this change by creating an easy to digest analysis on its subject. Even if renewable energy powered cooling was invented just yesterday, it has progressed further already today.

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